THE UPRUSH OF AIR NECESSARY TO SUSTAIN THE HAILSTONE

By W. J. HUMPHREYS

The upward velocity of the air necessary to just sustain a hailstone of a given size often has been computed on this or that set of assumptions. The most doubtful (in fact, distinctly erroneous) of these assumptions, the "drag"—that is, pull plus suction—of a steady wind on a sphere, can now be replaced by actual wind-tunnel measurements made at the Bureau of Standards and elsewhere.

From these measurements made in a steady wind of 150 foot-seconds and kindly supplied by the Bureau of Standards the following table has been computed on the assumptions that the drag varies directly (1) as the density of the air and (2) as the square of the wind velocity, and the further assumptions that (3) the density of the air is three-fifths that at sea level, corresponding to a height of about 5 km., that (4) the density of the hailstone is as given, from 0.91 nearly the maximum possible, to 0.5, certainly close to the minimum, and (5) that the stone is spherical.

Updrafts of air, of three-fifths its sea level density, sufficient to just sustain hailstones

Diameter of stone	Density of stone				
	0.9	0.8	0.7	0.6	0.5
Inches	*Miles per hour*	*Miles per hour*	*Miles per hour*	*Miles per hour*	*Miles per hour*
1	62	59	55	51	47
2	89	84	78	73	66
2.5	103	98	91	84	77
3	123	116	109	101	92
3.5	154	145	136	126	115
4	210	198	185	172	157
5	248	234	219	203	185

Hailstones 1 inch in diameter are very common, even on reaching the ground after some melting during their fall. Two-inch stones also are often reported, and even the 3-inch size is not extremely rare. The occurrences in the free air of approximately solid, spherical hailstones 4 inches in diameter is doubtful, though even much larger have been reported. One good reason for this doubt is the surprising experimental fact that the drag of a strong wind is decidedly less on a 4-inch sphere than on a 3-inch one, and not greater in about the ratio of their cross sections (16 to 9), as commonly supposed.

With reference to the navigation of the air, it is obvious from these values that the midst of a cumulus cloud in which large hailstones are being formed is an extremely dangerous place (apart from the lightning hazard and mechanical injuries by the hail) for aircraft of whatever type—a place to be avoided at every cost.

This statement is based on the assumption that the generally accepted theory of the formation of the hailstone (its suspension and uplift by rising currents until full size is attained) is sound.

It has been suggested that the larger hailstones are formed by the capture and freezing of undercooled water in the course of their fall. This may look like a simple way out of the necessity of assuming uprushes of hurricane velocity, but it is not tenable. In the first place we have no evidence whatever of the existence of appreciably undercooled raindrops, and even if they did exist large hailstones could not be formed in the manner suggested.

Suppose, for instance, that there is enough undercooled rain below the falling hailstone to produce a horizontal layer of water an inch deep, certainly an extravagant supposition, and suppose that every drop touched by the falling stone is captured and converted to ice—an unallowable supposition as explained below—what would be the thickness of the shell thus added?

If a is the fraction of the space in the layer of evenly distributed undercooled drops occupied by water, and r_0 the initial radius of the stone, then, clearly, the catch at any stage of the fall, $a\pi r^2 dh$, due to the infinitesimal change of height, dh, is equal to the corresponding volume added, $4\pi r^2 dr$, from which we have

$$dr = \frac{a}{4} dh$$

Hence the thickness of the shell gained by the stone in falling clear through the layer of undercooled rain is

$$r_1 - r_0 = \frac{a}{4}(h_0 - h),$$

in which h_0 and h are the heights of the top and bottom, respectively, of this layer.

But, according to the above assumption, the undercooled rain through which the stone falls is sufficient to make a horizontal layer of water 1 inch thick. That is,

$$a\ (h_0 - h) = 1 \text{ inch}$$

Therefore $r_1 - r_0$, or the thickness of the captured shell, is just one-quarter of an inch, on the assumption that all the captured water turns to ice.

However, as implied above, this assumption is not allowable. If the undercooling were, on the average, even as much as 10° C., the latent heat of fusion would prevent all but one-eighth of the water from freezing. Hence, under even these most favorable circumstances the thickness of the added shell could not be more than roughly one-thirtieth of an inch. Evidently, therefore, hailstones are not produced in this way, and we are, so far as we now can see, forced to assume uprushes of hurricane velocity for the production of very large hailstones. And that violent uprushes can and do occur in the atmosphere we know also from the remarkable feats of the tornado in lifting and carrying to considerable distances objects far more difficult to support than the largest authentic hailstones.